Open-circuit voltage optimisation of amorphous silicon thin film solar cells for flexible photovoltaics

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ABSTRACT: Amorphous silicon (a-Si:H) solar cells can be deposited in the substrate or n-i-p configuration, which allows the use of flexible substrates such as plastic sheets or metallic foils. In this work, we develop processes compatible with poly-ethylene-naphtalate (PEN) plastic foils and our investigations focus on a cell design that avoids V_{oc} losses on textured substrates. We introduce an amorphous carbide n layer (n-SiC) with a high band gap and show that this layer yields high open circuit voltage (V_{oc}) independent of the substrate micro-texture. Initial efficiencies of 9% on glass coated with hot silver and 8.8% on plastic substrate are achieved. Finally, the beneficial effect of the improved V_{oc} of the a-Si:H is incorporated into micromorph tandem cells fabricated on flexible substrates. The experiments with a n-SiC layer in the a-Si:H top cells result in the fabrication of micromorph tandem cells with initial efficiency of 10.9% on a low-cost PEN substrate, for an a-Si:H top cell thickness of 270 nm.
Keywords: a-Si, tandem, flexible substrates

1 INTRODUCTION

The n-i-p (nip) configuration has the potential to lower the cost of photovoltaics by allowing the use of flexible non transparent substrates such as plastic sheets or metallic foils. We focus our investigations on poly-ethylene-naphtalate (PEN) plastic foils. The major strengths of PEN are the cost per square meter which is lower than glass, the possibility to do the deposition in a roll to roll process which allows deposition of hundreds of meters of solar cell in one run [1, 6], and finally the light weight, reduced fragility and flexibility of the module which reduce the requirements on storage and transportation costs. The technology is ideal for companies that seek to be a cost leader in the future PV market.

The key element for further market penetration of these substrates is increasing the initial and stabilized efficiency. This can be achieved with tandem or multijunction solar cells [1, 2, 3, 8], such as micromorph cells and light trapping techniques [1] that allow the use of lower thickness and thus yield a lower degradation in amorphous cells, and also a reduced deposition time. Bailat et al. [1] has shown that the current density (J_{sc}) can be enhanced on plastic substrate but with a reduction of open circuit voltage (V_{oc}) and fill factor (FF). Here, we investigate two directions for increasing the V_{oc} on texture substrates, changing the substrate shape features or cell design with the aim of combining high J_{sc} and V_{oc} on plastic substrate.

Recently, Bailat et al. [3] showed that, in the case of p-i-n (pin) µc-Si:H cells, a slight modification of the surface morphology could lead to strong improvement of V_{oc}. We investigate the effect of these surface morphologies on nip a-Si:H cells.

In the second part, our investigations focus on a cell design that yields high V_{oc} on strongly textured substrates. The n-layer is crucial in nip solar cells because it is the first deposited layer. It can determine the electronic properties of the following layers such as the interface defects at the n/i interface. Microcrystalline n layers (n-µc) have given good results in the past, because they can be doped efficiently. Unfortunately, in terms of crystallinity, conductivity and thus Fermi level position, the quality of this layer depends to a large extent on the substrate material [9] and morphology. The incorporation of carbon into the doped layer increases the V_{oc} [12] and decreases the absorption loss in the n layer when compared to regular amorphous layers. Therefore, we introduce an amorphous carbide n layer (n-SiC) with a high band gap in order to reduce the influence of the substrate texture on the V_{oc}.

Finally, the beneficial effect of the improved a-Si:H on textured plastic can be directly incorporated into micromorph tandem cells (stack of microcrystalline µc-Si:H and a-Si:H) fabricated on flexible substrates. The limitation of micromorph comes usually from the lack of current in the a-Si:H solar cell. In order to match the current of the micromorph without further increasing the thickness of the a-Si:H absorber, we introduce an SiO based PECVD intermediate reflector which reflects part of the incoming light in the a-Si:H top cell. This strategy guarantees a low light induce degradation of the micromorph tandem thin film silicon.

2 EXPERIMENTAL

The PEN substrates are coated with Cr-Ag-ZnO stacks deposited by a roll-to-roll process in a large area multi-source sputtering system at the Fraunhofer Institut für Ionenstrahl und Plasmatechnik (FEP), Dresden [5]. For reference purposes and for cells development, we also use glass substrates (Schott AF 45) coated with Cr-Ag-ZnO deposited with our in-house sputtering system. The silver can be deposited at room temperature, in this case the surface of the layer is flat, or at high temperature where a partial crystallization of the layer results in a rough surface called “Hot Silver”. The chromium is an adhesion layer, the silver serves as back reflector and electrical contact for the solar cell and finally the ZnO protects the silicon layer form metallic atoms diffusion and enhances the optical matching of the back reflector [13].

The silicon films are deposited by plasma enhanced chemical vapour deposition, at very high excitation frequencies (VHF-PECVD, 50-150 MHz) on PEN or

glass substrates with opaque reflector. The main gases for the deposition are silane (SiH_4), hydrogen (H_2), methane (CH_4), phosphine (PH_3) and trimethylboron (TMB) for the n and p doped layers.

In order to keep the process fully compatible with PEN substrate, the deposition temperature is kept below 200°C. This limits the possibility to adjust the gap of the intrinsic layer. Nevertheless, the gap can still be tuned with the dilution ratio ($[H_2]/[SiH_4]$) [14]. In the following, the dilution of the a-Si:H i layer is 2 except when something else is specified.

The transparent front electrode is zinc oxide (ZnO) deposited by low pressure chemical vapour deposition (LP-CVD) [6]. It consists of boron doped ZnO deposited under conditions which result in a textured surface with an root mean square (RMS) roughness of about 70 nm for standard 2µm thick layer. Additionally, we developed new back reflectors where flat silver on glass or on PEN is coated with LP-CVD ZnO followed by a surface treatment similar to that described by Bailat et al. [3].

The current-voltage (IV) measurements are performed at 25°C under AM1.5 solar spectrum with a solar simulator (Wacom WXS-140S-10). From that IV curve the V_{oc} and FF were obtained. The external quantum efficiency (EQE) is measured with a spectral response setup. The EQE curve is given at short circuit condition except when something else is specified. The J_{sc} is calculated from the EQE by convolution with the AM 1.5 solar spectrum and by integrating over the wavelength range. This method avoids uncertainties in the determination of the solar cell surface area.

The area of the cells is typically 0.25 cm^2, completely isolated and made without encapsulation, antireflection coating nor silver grid on top of the front TCO.

3 SUBSTRATE MORPHOLOGY

In the first part of the paper, we investigate the effect of the surface morphology on the nip cell properties. We work with substrates where we can deliberately change dimension and shape of the surface roughness independently [15]: glass coated with silver and a rough LP-CVD ZnO, followed by a surface treatment. The design of the nip solar cell is kept as simple as possible. The structure is glass/Cr/Ag/LP-CVDZnO/n-µc/a-Si/p-µc/LP-CVD ZnO. The cell thickness is below 300 nm and here the dilution of the i layer is 6. Figure 1 shows the external quantum efficiencies (EQE) at a reverse bias voltage of -1V. Table 1 shows the V_{oc}, FF, J_{sc} at short circuit condition and with a reverse bias voltage (-1V) and efficiencies of cells with different surface treatment times of the ZnO, and of a flat cell for reference.

Table I: Solar cell parameters for back reflectors with different surface treatment time.

Surface treatment [min]	0’	15’	30’	45’	Flat
Efficiency	5.4	6.6	7.1	7.2	6.6
V_{oc} [mV]	710	772	821	846	888
FF [%]	59	66	69	69	67
Current [mA/cm^2]	13.0	13.0	12.6	12.3	11.0
Current (-1V) [mA/cm^2]	13.9	13.7	13.1	12.6	11.1

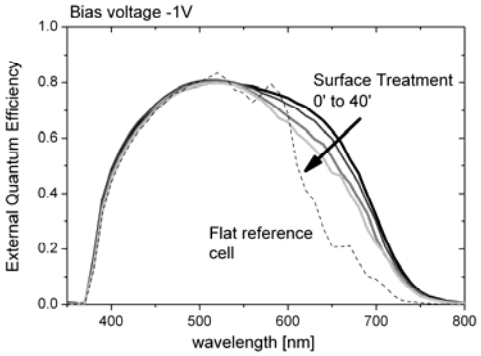

Figure 1: External Quantum Efficiency for different back reflector structures after different time of surface treatment of the LP-CVD ZnO (full lines) and a flat reference (dashed line)

The EQE are measured with a bias voltage of -1V in order to assess the optical characteristics of the substrates. Table 1 shows that for a given size of the ZnO texture, the treatment reduces the light trapping of the ZnO structure. On the other hand the improvement of V_{oc} and FF results in greatly improved efficiencies of the cells. For this series, a relative increase of efficiency of 33% is found with the surface treatment and 9% when compared to the standard flat substrate. The treatment changes the morphology of the substrate [3] and only slightly affects the RMS roughness [15]. Our results show that the shape of the substrate can lead to dramatic changes on the cell electrical characteristics of a-Si:H nip solar cells.

4 CARBIDE N-DOPED LAYER

In the second part of this paper, we evaluate the influence of the n layer on the V_{oc}. The state of the art nip solar cells are usually prepared with a n-µc layer deposited directly onto the substrate, as it is the case for the cells presented in figure 1. This configuration can give good results, because microcrystalline layer can be doped efficiently. However, we observed that the n-µc layers can have different properties depending both on the substrate material [9] and texture. This morphology effect can be seen in Table 1 where the surface treatment increases strongly the V_{oc} and decreases the difference in collection (EQE at 0V and -1V). It has also been shown that the conductivity in microcrystalline doped layers depends to a large extent on the thickness of the layer [16]. This has considerable consequences because in the solar cell optimization process, it is mandatory to reduce the thickness of doped layers in order to minimize the optical losses.

In this section, we present the development of an amorphous n layer which avoids most of the V_{oc} losses related to the substrate texture. This layer is developed with the addition of methane and thus it is an amorphous carbide n layer (n-SiC). It has been describe by Y. Hamakawa [12] that the carbon in the N layer increases the gap of the layer, the V_{oc} and the efficiency of the a-Si:H solar cell. Our n-SiC has a high band gap of 2.4 eV measured with the Tauc method.

Figure 2 compares the V_{oc} of nip solar cells with microcrystalline and carbide n layers on the LP-CVD ZnO with four surface treatment times. The cells have been deposited with all the other parameters like thickness and doping of the layer, front TCO and dilution kept constant. The trend lines show that the decrease in V_{oc} from strongly treated to untreated substrate is less pronounced for the n-SiC layer (full line) than for n-µc layer (dashed line). Even for the fully treated substrate, the n-SiC layer gives a better V_{oc} (900 mV) than with a microcrystalline layer (878 mV).

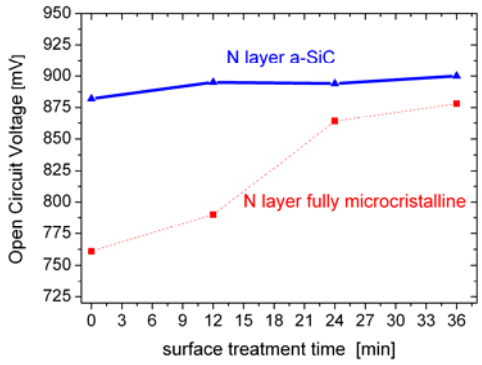

Figure 2: V_{oc} comparison of cells with a microcrystalline n-µc layer (dashed line) and the n-SiC layer (full line). The substrate is a rough LP-CVD ZnO with different surface treatment time.

5 AMORPHOUS SOLAR CELL

In the third part of the paper, we apply the findings of the previous section to flexible solar cells where the glass substrate has been replaced by PEN. The cells were deposited on a flexible structure: PEN / Cr / Ag / LP-CVD ZnO. The cells have the following structure:
Back Reflector /n-SiC/a-Si/p-µm-Si/LP-CVD ZnO. The optimum shape and size of the ZnO structure that was found on glass has been applied on PEN. The electrical characteristic of the cells are given in table 2 and the EQEs at short circuit condition are shown in figure 3. A flat PEN substrate and a glass "hot Silver" substrate are added for reference.

Table 2: Solar cell parameters for different back reflectors

Back reflector	ZnO LP-CVD	Flat	Hot Silver
Jsc [mA/cm2]	14.3	12.3	14.2
V_{oc} [mV]	888	895	915
FF [%]	70	66	69
Efficiency [%]	8.8	7.3	9.0

Our optimized LP-CVD ZnO textured back reflector exhibits a relative increase of 20% of efficiency for the textured substrate compared to flat substrate. The result shows an initial efficiency of 8.8% for an a-Si:H cell on PEN substrate. For comparison 9% initial efficiency is obtained on glass substrate with hot silver with a V_{oc} of 915 mV.

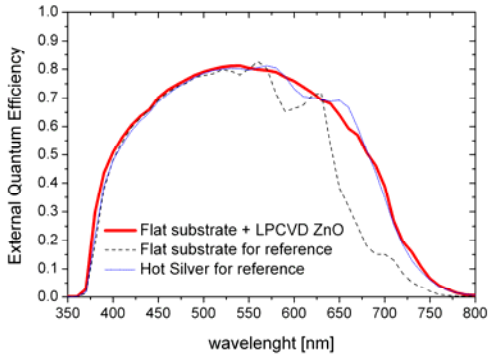

Figure 3: External Quantum Efficiency of nip a-Si:H on a flat (dashed line), textured PEN substrate (full line) and a glass hot silver for reference (small dashed line)

6 Micromorph solar cell

Finally, we apply the results obtained with the a-Si:H solar cell into a miromorph cell preparation, including both optimised back-reflectors and with taking into account the development of the n-SiC layer. The thickness of the microcrystalline and amorphous silicon solar cell is 1.2 µm and 270 nm, respectively. Our best initial characteristics of micromorph solar cell on PEN substrate are V_{oc} = 1.35 mV, FF = 71.5 %, J_{sc} = 11.3 mA/cm^2 and an efficiency of 10.9%.

Our results show that our n-SiC layer is capable of providing high V_{oc} in the tandem structure. At present the tandem is top limited with currents of 11.3mA/cm^2. Our future efforts are directed towards improved matching by using an intermediate reflector between the top and bottom cell as suggested by D. Fischer [18]. Here, we utilize an intermediate reflector SiO based fabricated in situ by PECVD as described by P. Buehlman [17].

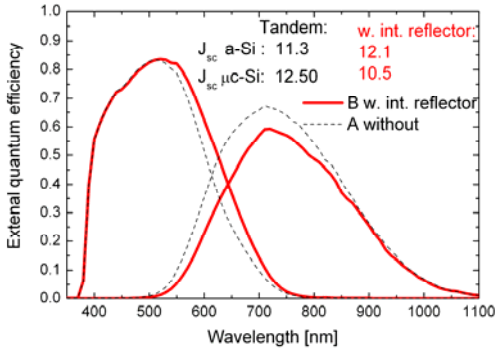

Figure 4: External Quantum Efficiency of a tandem micromorph solar with (dashed lines) and without intermediate reflector (full lines).

Figure 4 shows the EQE and Table 3 summarizes the parameters of micromorph with and without intermediate reflector. For assessing the optical properties, we keep the thicknesses of the respective absorbers constant. A current of 12.1 mA/cm^2 can be achieved in the top cell with the intermediate reflector while keeping intrinsic layer thickness of 270nm in the a-Si:H cells. In order to

match the current densities, we plan to increase the bottom cell thickness which is possible without compromising stability. A remaining drawback is the loss of 1.2 mA/cm^2 in the total current which will require further optimisation of the intermediate reflector.

Table 3: Tandem cells w/o intermediate reflector

Cell Intermediate reflector	A without	B with
J_{sc} [mA/cm2] a-Si:H	11.3	12.1
J_{sc} [mA/cm2] mc-Si:H	12.5	10.5
V_{oc} [mV]	1.37	1.36
FF [%]	67	68
Efficiency [%]	10.4	9.7

7 DISCUSSION

The development of the nip solar cell on our back reflector consisting of flat Ag and LP-CVD ZnO gives valuable insight into the effect of the substrate texture on optical and electrical properties of nip solar cells. This substrate reduces texture mediated plasmon absorption in the metallic back reflector and thus diminishes the optical losses, but thanks to the LP-CVD ZnO it supplies a sufficient amount of roughness for light trapping in the absorber. Moreover, it has been reported in a pin solar cell [19] that the configuration with a smoothed back reflector, metal deposited on a flat surface, has optical advantages compared to a rough back reflector, metal deposited on a rough surface.

The first part of the paper shows that the optimum morphology, for the a-Si:H solar cell is the heavily treated substrate with 45 minutes of plasma treatment. The treatment shows a big improvement of efficiency with a 33% relative increase of efficiency compared to an untreated substrate. Nevertheless, the treatment reduces strongly the current gain compared to a flat substrate. Our path toward further increase of the efficiency is to tune the cell design in order to keep good V_{oc} and FF properties on a slightly treated substrate. In other words, the goal is to reduce the optimum treatment time in order to keep the benefits of light trapping from the texture.

Our results show that, even for simple single-junction a-Si:H devices, a complex interplay between substrate morphology, chemistry and subsequent n layer takes place. It has been shown in the past that thin microcrystalline layers are sensible to the substrate material and we clearly find that it is also sensible to the morphology of the substrate.

Our amorphous n-SiC layer is less sensitive to the substrate morphology and material where the nucleation takes place. Furthermore, the n-SiC layer achieves very good results on textured substrates. We show that high V_{oc}, over 900 mV with low dilution ratio ($[H_2]/[SiH_4]$ = 2), can be achieved on textured substrate. The carbide layer is robust on different morphologies and it gives better results than a microcrystalline n layer. This cell design achieves clearly both, good light trapping and good V_{oc} and thus high efficiency thin film solar cell in the nip configuration.

Finally, we show that amorphous solar cell with 8.8% efficiency and micromorph tandems with 10.9% can be achieved on PEN substrate. The V_{oc} optimization is a pillar that allows us to achieve these results. Further strong improvements can be achieved with a better matching of the current in the micromorph tandem. The in-situ PECVD intermediate reflector can clearly increase the current of the top cell without increasing further the absorber thickness of the a-Si:H and this will limit the degradation of the tandem. In the near future, it is expected to achieve stable micromorph over 10% on plastic by combining the optimization of the substrate, cell design and the in-situ intermediate reflector.

8 CONCLUSION

In this paper, we present a way toward high V_{oc} on texture substrates and demonstrate the optimization of a nip a-Si:H solar cell on flexible substrate. We show that good light trapping and tandem structures can be applied on PEN substrate to increase the efficiency of the cells. We achieve a-Si:H and micromorph solar cells with 8.8% and 10.9% initial efficiency, respectively, on PEN substrate with amorphous and microcrystalline cells thickness of 270 nm and 1.2 μm, respectively, and guaranteeing low light induced degradation.

9 ACKNOWLEDGEMENTS

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